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Abstract. A theoretical, representative agent economy with a depletable resource stock, polluting emissions and productive capital is used to contrast environmental policy, which internalises externalised environmental values, with sustainability policy, which achieves some form of intergenerational equity. The obvious environmental policy comprises an emissions tax and a resource stock subsidy, each equal to the respective external cost or benefit. Sustainability policy comprises an incentive affecting the choice between consumption and investment, and can be a consumption tax, capital subsidy or investment subsidy, or combination thereof. Environmental policy can reduce the strength of sustainability policy needed. More specialised results are derived in a closed economy with a non-renewable resource, and in a small open economy with no environmental effects on utility.

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1. Introduction

In the voluminous government literature on sustainable development that has poured forth since the Brundtland report (WCED 1987) popularised the idea, it is often hard to distinguish sustainability policy from environmental policy. A document on a country's approach to sustainable development often starts with general statements about sustainability as safeguarding the well-being of future generations, but then continues with little more than a description of environmental policies. Detailed policies are spelt out on air and water pollution, solid waste, traffic congestion, habitat and biodiversity protection, etcetera, perhaps with special emphasis on the enduring nature of some forms of environmental damage. Nothing is said, however, about other policies that may be necessary or desirable to sustain well-being.

If governments truly believe that there are fairly imminent limits to the substitutability of human-made capital and knowledge for environmental resources, then this implicitly "strong" approach to sustainability, which treats environmental protection as the essence of sustainability policy, would be logical. But by the very limits of their environmental policies, most governments reveal that they do not much believe in such limits to substitutability. Most implicitly place finite rather than infinite values on marginal declines in environmental resources. So it seems relevant to current policy debate to at least explore the neoclassical or "weak" approach to sustainability here, and assume capital-resource substitutability at the margin. However, we express no view on the very uncertain questions of where limits to substitutability do actually exist. At the macroeconomic level, these are hugely difficult empirical questions which have so far eluded any answers which command consensus. This is why we write about what governments believe, rather than what is true. Neither do we give any view on what should be the appropriate policy response to such uncertainties.

Within the confines of our substitutability assumptions, we will confirm here the intuition that if it is needed at all, sustainability policy should include non-environmental aspects of providing more for future generations, such as encouraging more saving and hence capital investment to substitute for some degree of future environmental resource depletion. Sustainability and environmental policies will thus be at least partially distinct. The aim of this paper is to clarify these distinctions, using a conventional theoretical framework of a dynamic, deterministic, optimising economy with identical agents, represented by one agent making decisions in continuous time.

To do this, we must define the two types of policy more precisely. *Environmental policy* here is the time path of all incentives, such as emission taxes and resource conservation subsidies, with which the government can intervene in decentralised markets to internalise the costs that a single agent treats as external to her private maximisation of intertemporal welfare. The policy thus achieves the socially welfare-maximising ('optimal') path of development based on current individual preferences. We do not enquire into, and our theoretical model will not distinguish, when and why emission standards or tradeable permits might be preferable to taxes and subsidies, or what are the efficiency gains of taxes or tradeable permits over standards.

By contrast, *sustainability policy* is the time path of incentives which persuade agents in a decentralised economy to achieve a collectively-desired "sustainability" goal. We thus do not include government taxation of resource rents to fund public investment, for example in trust funds, in our range of policy instruments. The sustainability goal is viewed here as any departure from maximising social welfare based on current agents' own individual time preferences, that is aimed at improving intergenerational equity. Reasons for such a departure will be discussed, but not resolved, below.

As our analysis will clarify, if various policy interventions together achieve any general sustainability goal with intertemporal efficiency (meaning that the interventions must include internalising externalities), then they will effectively change the utility discount rate path, from what agents choose individually to some different, usually lower, path. This is so even when the fundamental goal of sustainability has nothing to do with the discount rate. For example, the goal could be ensuring that utility remains non-declining or sustainable, either of which might be regarded as a natural expression of "safeguarding the well-being of future generations". However, if a sustainability policy is achieving inefficiently, then the economy with policy intervention cannot be analysed as one with a different effective discount rate. The lack of consensus on any precise sustainability goal, and the analytical differences between efficient and inefficient ways of achieving it, means that the overall focus of sustainability policy will be unavoidably less uniform here than that of environmental policy.

The literature relevant to environmental policy and sustainability policy as we have defined them is wide-ranging, and identifying our contribution requires a detailed review which occupies most of the next section. At the end is the usual outline of the paper’s organisation.

2. Literature relevant to environmental and sustainability policies

A broadly similar distinction to that sketched above between environmental policy and sustainability policy was envisioned long ago:[1]

> "...the appropriate instruments to use for obtaining more equitable [intergenerational] distribution of welfare...are general instruments, for example, monetary policy directed at changing the market rate of interest. ... (Obviously, prior to using such

1. I thank a referee for pointing this out.

general instruments, policies directed at correcting inefficiencies in the allocation of resources...have to be adopted.)" (Stiglitz 1979, p61)

However, the formal (neoclassical) economic literature on "sustainability" that has sprung up since the late 1980s has mostly focused on defining and justifying it,[2] or on measuring it,[3] rather than on identifying policies to achieve it, which is our focus.

Nevertheless, there is plenty of literature about environmental and/or general intergenerational policies in a dynamic economy, which unless otherwise stated uses an overlapping generations rather than a representative agent (RA) demographic format for society. For our purposes, it is relevant to divide this literature into four parts. First, papers like John and Pecchenino (1994) and Smulders (2000, in RA format) provided analysis only from the viewpoint of a social planner. Thus no policy instruments as such were considered; though John and Pecchenino set the "golden rule" goal of maximising steady state utility, and Smulders noted whether or not consumption (and thus utility) rose or fell on a steady state path. Second are papers which considered a dynamic instrument of environmental policy to internalise externalities, but either no explicit sustainability goal (as in Bovenberg and Smulders 1995, Mohtadi 1996, both in RA format, and

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2. See for example Howarth (1992), Dasgupta (1994), Chichilnisky (1996) and Asheim, Buchholz and Tungodden (2001). Solow (1993, p171) made the goal of a sustainability policy clear, with his claim that "...we owe to the future a volume of investment that will compensate for this year's withdrawal from the inherited stock". However, he did not analyse what policy instruments can achieve this volume of investment if market forces do not.

3. See for example Pearce and Atkinson (1993), Asheim (1997), Aronsson et al (1997), Atkinson et al (1997), Brekke (1997), Weitzman (1997) and Hamilton and Clemens (1999).

Jouvet et al 2000), or no policy to achieve this goal (John et al 1995, which again adopted a golden rule goal for the social planner). Third are papers like Howarth and Norgaard (1990), Mourmouras (1993) and Krautkraemer and Batina (1999), which analysed some kind of sustainability goal, but had no conventional externalities, and hence no environmental policy.

Finally there are papers which considered both environmental policy and sustainability policy. Howarth and Norgaard (1992), Marini and Scaramozzino (1995), Howarth (1998), Bovenberg and Heijdra (1998) and Gerlagh and Keyzer (2001) all used an overlapping generations format; this allows the use of intergenerational transfers as a key instrument of sustainability policy, in pursuit of goals such as maximising the undiscounted sum of generations' lifetime utilities. Such transfers will not be available here because of our RA format. Becker's (1982, in RA format) instrument to achieve maximum constant utility was direct manipulation of the interest rate path, which we exclude: it would be difficult to sustain in a small open economy, and in any case is not easy to reconcile with the use of interest rates for macroeconomic stabilisation. The analysis in Pezzey (1989) foreshadowed that here, but was much simpler and more restricted.

What is new about our treatment, in comparison to this existing literature on both environmental policy and sustainability policy, is the combination of the following features. Pollution, resource depletion and physical capital accumulation are all included. Compared to much literature, our functional forms are more general. The focus is mostly on transitional rather than steady state paths. It is noted how applying environmental policy may reduce the strength of sustainability policy (for example, the rate of tax or subsidy) that is needed. Finally, of many policy instruments considered, the natural ones to use for sustainability policy in an RA format, at least in theory, turn out to be a capital subsidy, an investment subsidy, or a falling consumption tax rate, any of which encourage saving now and consuming later. Our focus on encouraging saving as a sustainability policy is supported by empirical measurement studies following the example of Pearce and Atkinson (1993), as acknowledged by discussion in Hamilton and Clemens (1999, Section V), but has so far received little theoretical attention. Our approach also allows us to investigate two more specialised topics also of possible interest to policymakers. One is whether on their own, resource incentives such as depletion taxes can prevent unsustainability in an economy with non-renewable resources. The other is what effect sustainability policy has on resource management and domestic production in a small open economy.

The rest of the paper is organised as follows. Section 3 contains the main results. It first describes the simple economy to be considered, after giving reasons why neither a more complex economy nor a fully general economy would serve our purposes. Environmental externalities in the model are highlighted, and a rationale for sustainability policy intervention is discussed but not formally analysed. The required environmental policies needed to internalise all externalities, and sustainability policies needed to achieve an intergenerational equity objective, are then derived from a unified analysis; and interactions between environmental and sustainability policies are considered. Section 4 uses an example economy with specific functional forms to show a precise effect of environmental policy on sustainability policy. Using minor modifications to the simple economy, Section 5 considers the two more specialised topics just mentioned. Section 6 concludes. Omitted algebraic calculations, flagged by "it can be shown that...", are available on the author’s website, http://cres.anu.edu.au/~pezzey.

3. Environmental policy and sustainability policy in a simple economy

3.1 The economy

A very general, representative-agent, continuous-time, deterministic economy would be similar to that in Asheim and Weitzman (2001). At any time $t \geq 0$, there would be a "consumption" vector $\mathbf{C}(t)$ of everything, including environmental amenities, that influences the representative agent's instantaneous utility $U(\mathbf{C}(t))$. Likewise, there would be a vector $\mathbf{K}(t)$ (generally with a different number of elements to $\mathbf{C}$) of stocks of built, knowledge and human capital, and of all environmental resources. The relationship between $\mathbf{C}$ and $\mathbf{K}$ would be given by a convex production possibilities set $\Pi\{.\}$:

$$[\mathbf{C}(t),\dot{\mathbf{K}}(t)] \in \Pi\{\mathbf{K}(t)\} \qquad [1]$$

However, the form of [1] is *too* general for our purposes. It hides specific features that make environmental resources important to policymakers. In [1] one cannot distinguish a human-made capital stock (whose increase is directly enabled by lowering utility) from a natural resource stock (whose increase is directly enabled by lowering production), renewable from non-renewable resources, flow from stock pollution, abatement from consumption expenditure, or external effects on utility from those on production. Almost all dynamic, economy-environmental models that address policy issues therefore include more specific features,[4] and we will do the same here. But to avoid unnecessary complexity, we mainly use a simple model that includes only the minimum features needed for the basic points we wish to make about sustainability policy and environmental policy. For example, the

4. We have in mind models like those in Hartwick (1990), Maler (1991), Hamilton (1994), Vellinga and Withagen (1996) and Sefton and Weale (1996).

simple model has no foreign trade, but in a final section we consider a small, open economy, so as to explore the different effects of sustainability policy in an economy with exogenous prices. We will note where points being made have wider applicability, as shown by an earlier version of this paper (Pezzey 2001) which used more complex models.

All variables in our simple model are time-dependent, but to reduce clutter we show this only where needed for clarity. The model is closed, with a stock S at continuous time t of a depletable, natural resource. The resource grows naturally at a stock-dependent rate $G(S)$ (though G could be zero for the case of non-renewable resources) and depleted at rate R, so

$$\left.\begin{array}{l}\dot{S}\ \ (:= dS/dt)\ = G(S) - R;\ \ S(t) \geq 0;\ \ S(0) = S_0 > 0, \text{ given;} \\ G_S\ \ (:= \partial G/\partial S)\ > 0 \text{ assumed for the economy's operating range}\end{array}\right\} \quad [2]^{5}$$

The other stock in the economy is productive capital K, which increases at rate of investment I (capital depreciation makes no difference to our results, so it is excluded):

$$\dot{K} = I; \qquad K(t) \geq 0;\ \ K(0) = K_0 > 0, \text{ given;} \qquad [3]$$

Transient, polluting emissions E depend positively on resource depletion (and use in production) R, and negatively on abatement current expenditure

5. It would be more realistic to have many natural resources, and to distinguish non-renewable from renewable ones. However, with many renewable resources, their ecological interactions (where the stock S^i of one resource affects the growth G^j of another resource, so that the scalar G_S is replaced by a matrix $\{\partial G^j/\partial S^i\}$) would cause big complications in calculating stock effects, but add little further insight.

a.[6] Production F of a consumption-investment good depends positively on productive capital and resource depletion, and negatively on emissions, and there is no exogenous technical progress. Production is divided among consumption C, investment and abatement spending:

$$\left.\begin{array}{l} F[K,R,E(R,a)] = C + I + a \\ F_K,\ F_R > 0,\ F_{KK},\ F_{RR} < 0,\ F_{KR} > 0,\ F_E < 0,\ F_{EE} < 0,\ E_R > 0,\ E_a < 0 \end{array}\right\} \quad [4]$$

Instantaneous utility U depends positively on consumption and resource stock, and negatively on emissions:

$$\left.\begin{array}{l} U = U(C,S,E) \\ U_C,\ U_S > 0,\ U_{CC},\ U_{SS} < 0,\ U_{CS} \geq 0,\ U_E < 0,\ U_{EE} < 0,\ \lim_{t\to\infty} U_C = 0. \end{array}\right\} \quad [5]$$

Lastly, the economy collectively implements an intertemporally efficient path in the interests of the current generation, and to do this it chooses consumption C, abatement current expenditure a, and resource depletion R *as if* to maximise (intertemporal) welfare $W^\rho(0)$. This is defined as the present value of utility, using a (perhaps constant) discount rate $\rho(t)$:

$$W^\rho(0) := \int_0^\infty \exp[-\textstyle\int_0^t \rho(z)dz]\ U[C(t),S(t),E(t)]\ dt; \quad \rho(t) > 0. \qquad [6]^7$$

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6. Contrast this with Bovenberg and Heijdra (1998), where the "dirty" variable creating emissions is the capital stock, and Jouvet et al (2000), where the dirty variable is output. In both papers, a positive tax on capital is desirable for environmental reasons.

7. When the discount rate ρ is not constant, calling W^ρ "welfare" as here is a convenient name, already found in the literature. But it can have awkward implications, since the economy's fundamental intertemporal criterion may then have nothing to do with maximising W^ρ. For example, $W^\rho(t)$ (defined below in Section 3.3(iii)) *rises* over time on the maximum *constant* consumption path in Solow (1974). So formally, W^ρ is better regarded just as what the economy acts *as if* to maximise.

With Ψ^K and Ψ^S as co-state variables, the current value Hamiltonian for maximising welfare [6] subject to conditions [2]-[5] is then

$$\begin{aligned} H &= U + \Psi^K\dot{K} + \Psi^S\dot{S} \\ &= U[C,S,E(R,a)] + \Psi^K[F(K,R,E(R,a)-C-a] + \Psi^S[G(S)-R] \end{aligned} \qquad [7]$$

All functional forms in [2]-[5] are assumed to be as smooth and convex as is needed for the existence of a unique and interior development path which maximises welfare. This will be called "optimal", or "socially optimal" if this needs to be distinguished from private optimality as defined below. The context will make clear if the discount rate ρ is constant.

3.2 Principles of environmental policy

We define the economy's environmental policy as the time path of price incentives which the government must create, to induce an individual agent in a decentralised equilibrium to follow the socially optimal path based on her own time preferences. Policy intervention is needed because the agent is presumed to maximise welfare $W^p(0)$ imperfectly, by ignoring (externalising) the public or "environmental" effects of her actions when making marginal choices of control variables. The result of these choices is called the "privately optimal" path. The externalised effects selected here are the partial derivatives of utility with respect to the environmental resource stock, U_S, and emissions, U_E; of production with respect to emissions, F_E; and of resource growth with respect to the stock, G_S. This covers a good range of effects, but many other selections could be made. For example, to model pollution by greenhouse gases, one would have to model a world (rather than economy-level) resource or cumulative pollution stock, since that is what affects utility or production. Or if renewable resources are privately owned, there would be no reason to suppose that G_S

is externalised. Also, externalities from human-made resources like knowledge or education could be treated by similar techniques, but by convention are not included in environmental policy.

An environmental policy incentive $\{\tau^i(t)\}$ is a tax when positive and a subsidy when negative, and both can occur at different times for the same incentive. Importantly, any net revenue from (or cost of) the incentive system is assumed to be immediately refunded to (or taxed from) the representative consumer as a lump sum which does not affect any marginal choices. (To do otherwise, by including government spending and unbalanced budgets, and by excluding lump sum transfers, would significantly alter our analysis.) To institute these incentive schemes credibly for all time would be difficult, but along with most optimal control modelling, we do not explore what constitutional innovations this might require in a democratic society. Neither do we consider the well-known political difficulties of collecting the lump sum taxes needed when the incentive scheme has net costs, or the administrative difficulties of managing tax rates that vary over time.

As for the choice of incentives, we confine ourselves to simple proportional taxes. (For brevity, a "tax" is hereafter indeterminate in sign unless otherwise stated, so it could be either a conventional tax, or a subsidy.) We thus do not consider quantity restrictions (whether tradeable or non-tradeable),[8] and ignore the bands of different rates found in many real-world tax schedules. There are still at least seven instruments available: taxes on consumption (τ^C), capital (τ^K), investment (τ^I), abatement current

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8. Mohtadi (1996, Section 3.3) considers a quantity restriction which increases emissions abatement, but this is modelled as a "mandatory change in a parameter value", whereas here we have an explicit emission flow which can be taxed.

spending (τ^a), resource extraction (τ^R), resource stock (τ^S), and emissions (τ^E).

Of these, the consumption tax and the investment tax can be shown to be substitutes for each other, and expressions for the first are simpler than for the second. So we consider only the consumption tax in our main analysis, though in Section 3.4 we will report a basic result for an investment tax. We will also mainly ignore a tax on the capital stock, which is another, and in fact algebraically simpler, substitute for a consumption tax, though arguably much harder to administer. Both an abatement tax and a tax on resource depletion turn out to be theoretically redundant, but we consider them here because they are realistic policy options, and it is worth showing their redundancy explicitly.

The private individual thus perceives a utility function

$$U = U(C,\bar{S},\bar{E}(R,a)) \qquad [8]$$

and accounting relationships

$$\left.\begin{aligned} \dot{K} &= F(K,R,\bar{E}(R,a)) - C - \dot{K} - a - (\tau^C C+\tau^a a+\tau^R R+\tau^S S+\tau^E E - \Omega) \\ \dot{S} &= G(\bar{S}) - R \end{aligned}\right) \qquad [9]$$

where overbars mark the environmental variables $\bar{S}$ and $\bar{E}$ that individuals ignore when making private, maximising choices, and Ω is the lump sum refund of all net tax revenues that balances the government’s budget.

3.3 Principles of sustainability policy

It will turn out that the same analysis gives results for instruments of both environmental and sustainability policies if these policies are applied together. So before the analysis, we must clarify the goal of sustainability policy, building on the discussion in the Introduction. Whatever it is, the sustainability goal must be ethically motivated by considerations of intergenerational equity, and must require some departure from the social maximisation of welfare W^p in [6] using the representative agent's discount rate $\rho(t)$. Sustainability policy is meaningless as a distinct concept in the neoclassical context unless one accepts that a government can act as a benevolent cross-generational dictator, and seek a policy which may not maximise W^p.

Whether or not such a policy is considered schizophrenic, and whether or not it can be democratically supported by the "people", namely the current generation who seek (albeit imperfectly) to maximise W^p in their private choices, are important questions in the economics of sustainability which have not yet been fully resolved. One could just appeal to Marglin's (1963, p98) idea that "...the Economic Man and the Citizen are for all intents and purposes two different individuals", and identify Economic Man as the private welfare maximiser, and the Citizen as the supporter of sustainability as a public policy goal. More satisfying would be to develop the informal idea in Daly and Cobb (1989, p39) and Howarth and Norgaard (1993, p351) that sustainability is a partly-public good, because of the sexual intermixing of bequests across successive generations. We do not add any analysis here, and just accept that sustainability policy aims at some notion of intergenerational equity that is not captured by the welfare function W^p.

This deliberately leaves the exact goal of sustainability policy undefined, though of the several possible goals, three which make sense in our neoclassical economy are:

(i) achieving constant utility (after Solow 1974 and Hartwick 1977);

(ii) avoiding any decline in utility, by ensuring utility is always sustainable (after Pearce et al 1989 and Pezzey 1989);

(iii) avoiding any decline in welfare $W^{\rho}(t)$ from time t onwards, defined as $\int_t^{\infty} \exp[-\int_t^s \rho(z)dz]\ U[C(s),S(s),E(s)]\ ds$, after Riley (1980).[9]

Choosing any or none of these three goals is however less important here than knowing how the sustainability goal relates to the socially optimal and privately optimal paths of the economy. Three main alternatives are:

(a) The sustainability goal is met on the privately optimal path, without policy intervention, leaving no need for sustainability policy as such.

(b) The goal is met on the socially optimal, but not on the privately optimal path. (The converse is logically possible, but unlikely.) Environmental policy will then achieve sustainability as an automatic side-effect.

(c) The goal is met on neither the privately optimal nor the socially optimal path. To achieve sustainability, there must then be a binding sustainability policy instrument distinct from the instruments of environmental policy. *This is the main case we consider hereafter*.

Having assumed the need for a binding sustainability policy, we will also usually assume that the policy is enacted at the same time as environmental policies, so that the overall result of intervention is an (intertemporally) *efficient* path of development. In fact, we then further assume that the sustainability goal is reached *optimally*, that is, with minimum loss of

9. Non-declining wealth or non-declining aggregate capital, two further well-known alternatives suggested by Pearce et al (1989), are best viewed in our context as (possibly flawed) means, rather than fundamental ends, of sustainability policy.

welfare W^{ρ}, but this stronger assumption (which of course implies efficiency) is not needed for our analytical result.[10] From Takayama (1985, p188), on an efficient sustainable path, the economy acts *as if* it maximises *some* present value measure, say $W^{\sigma}(0)$, using a "sustainable discount rate" path σ(.) in place of ρ(.) in [6]:

$$W^{\sigma}(0) := \int_0^{\infty} \exp[-\int_0^t \sigma(z)dz]\ U[C(t),S(t),E(t)]\ dt; \quad \sigma(t) > 0. \qquad [10]$$

The rate $\sigma(t)$ roughly reflects whatever degree of intergenerational equity society collectively wants, but the "roughly" qualifier is important. If the fundamental or primitive sustainability goal is, say, constant utility, which in itself has nothing to do with discount rates, then the path of $\sigma(t)$ is not fundamental. Changes in the economy's production or utility parameters would make such a goal harder or easier to achieve, and thus require a greater or lesser departure of $\sigma(t)$ from $\rho(t)$.

A complication met in Sections 4 and 5.1 below is that a sustainability policy on its own, either without accompanying environmental policies in an economy with externalities, or using an inappropriate instrument, will be inefficient. Such a policy cannot be represented as a change in the effective discount rate path from $\rho(t)$ to $\sigma(t)$. However, it may be of some interest, and to illustrate an inefficient sustainability policy, we choose either constant utility or non-declining utility as the goal in such cases.

3.4 Combined analysis of environmental and sustainability policies: the set of optimal sustainability policies

We have just noted that when environmental and sustainability policies are applied together in a way that minimises the loss of present value caused by

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10. As an example of the difference, if the sustainability goal is non-declining utility, then achieving maximum constant utility will be efficient, but may not be optimal.

the sustainability goal, the resulting optimal sustainable path satisfies first order conditions identical to those for the socially optimal path, except that $\sigma(t)$ replaces $\rho(t)$. So we can analyse both policies together by comparing the socially optimal W^σ-maximisation path, still derived from the Hamiltonian [7], with the privately optimal path with policy intervention. The Hamiltonian for the latter is denoted $\tilde{H}$ and formed from the perceived utility function [8] and accounting relationships [9], with $\tilde{\Psi}^K$ and $\tilde{\Psi}^S$ as the new co-state variables, and with it understood that the individual discount rate $\rho(t)$ is used:

$$\begin{aligned}\tilde{H} &= U(C,\bar{S},\bar{E}(R,a)) + \tilde{\Psi}^K[F(K,R,\bar{E}(R,a))-C-a] \\ &\quad - \tilde{\Psi}^K[\tau^C C+\tau^a a+\tau^R R+\tau^S S+\tau^E E(R,a)-\Omega] + \tilde{\Psi}^S[G(\bar{S})-R]. \qquad [11]\end{aligned}$$

Formulae for the set of policy instruments τ^C, τ^R, τ^S and τ^E come from comparing the first order conditions of the two optimal paths. (To consider environmental policy alone, we just set $\sigma(t)$ equal to the individual discount rate $\rho(t)$ when manipulating the Hamiltonian H for the socially optimal solution.) Appendix 1(a)-(c) shows that the obvious, sufficient optimal sustainability policy at any time is then the combination, with all quantities as measured on the optimal sustainable (W^σ-maximising) path, of:

Environmental policies

$$\tau^E = -1/E_a = -(U_E/U_C + F_E) > 0 \qquad [12]$$

$$\tau^a = 0 \qquad [13]$$

$$-\tau^S = U_S/U_C + (F_R-\tau^E E_R)G_S = U_S/U_C + [F_R+(U_E/U_C+F_E)E_R]G_S > 0 \qquad [14]$$

$$\tau^R = 0 \qquad [15]$$

Sustainability policy

$$-\dot{\tau}^C/(1+\tau^C) = \rho-\sigma \qquad [16]$$

The intuition behind the environmental policies is simple. Tax τ^E internalises the two external costs of emissions, measured in consumption units: $-U_E/U_C$, the amenity cost, and $-F_E$, the productivity cost. Subsidy $-\tau^S$ internalises the two consumption-valued, external benefits of the resource stock: U_S/U_C, the amenity benefit, and $G_S(F_R-\tau^E E_R)$, the benefit from faster resource growth, valued at price minus user cost. Both an abatement subsidy τ^a and a resource tax τ^R are not needed in theory (though they may be in practice, if abatement spending or resource flows are much cheaper to measure than emissions or resource stocks, respectively). From this simple example, and more complex examples with trade, resource extraction costs, etcetera reported in an earlier version of this paper (Pezzey 2001), one can be confident that "internalise all externalities at their source" is a useful general rule for dynamic environmental policy. (Important exceptions to this would be the case of international interactions and cross-border externalities, or when time-varying incentives and lump sum taxes are not available.)

On another practical note, the U_E/U_C and U_S/U_C terms in [12] and [14] would typically be measured in dollars per tonne of emissions or resource stock. Data for them would have to come from the same, difficult, non-market valuation exercises required for other methods of resource accounting and sustainability measurement. The non-measurability of the separate partial derivatives of utility involved here does not add any extra difficulty to these exercises, contrary to a claim in Pearce et al (1989, p49, note 3).

The intuition behind the sustainability policy [16] can readily be seen if discount rate σ is always strictly less than ρ, so that σ expresses stronger concern for future generations than ρ. $\tau^C(t)$ would then be a falling consumption tax or rising consumption subsidy, which gives an incentive to delay consumption and bring forward productive investment. It would change an individual's effective utility discount rate from ρ to σ, and so would be almost a way of achieving Becker's direct manipulation of this rate. Sustainability policy looks different in overlapping generations models, because the latter assume the feasibility of lump sum intergenerational transfers, which can shift consumption to the future without the use of incentives that directly affect the consumption-investment decision.

As noted earlier, sustainability policy instruments other than a consumption tax are available, though all instruments act to influence the consumption-investment decision towards less consumption and more investment in the early stages of development. In Appendix 6 we show that if a capital tax τ^K as well as a consumption tax τ^C were to be used, [16] would be replaced by

$$-\dot{\tau}^C/(1+\tau^C) - \tau^K = \rho-\sigma.$$

If an investment tax τ^I were then to be used instead of the consumption tax, substituting $C = F - (1+\tau^I)I - \tau^K K - \tau^a a - \tau^R R - \tau^E E - \tau^S S + \Omega$ throughout and using investment I as a control variable can be shown to give

$$(\dot{\tau}^I - \tau^I F_K - \tau^K) / (1+\tau^I) = \rho-\sigma.$$

So in terms of algebra, a capital tax is simplest while an investment tax is most complicated, though this says nothing about which of the three taxes would be simplest to administer in practice.

3.5 The interaction of environmental and sustainability policies

Despite the neat algebraic separation between environmental policies in [12]-[15] and sustainability policy in [16], the two sets of policies are part of the same dynamic general equilibrium, and so must interact. The sizes of emission tax and resource subsidy that are required to maximise welfare in the presence of the sustainability policy [16] needed if $\rho-\sigma > 0$ at all times, must generally differ from the tax and subsidy levels required when

$\rho-\sigma = 0$ and no sustainability policy is needed, even though formulae [12]-[15] remain unchanged. This parallels the key result, found in the overlapping generations context by Howarth and Norgaard (1992), that environmental valuations (here the sizes of τ^E and $-\tau^S$) do not exist in a vacuum, independently of society's view on intergenerational equity (here the size of $\rho-\sigma$).

There will also be an interaction in the other direction, in that whether or not environmental policy is actually implemented will affect the strength of sustainability policy needed to reach a goal defined in terms of utility change. However, we then need to compare efficient sustainability policy with inefficient sustainability policy, and the above results do not apply to the latter. So it is only in simple cases with specific functional forms, as illustrated next, that we can be clear about the sign and size of interactions.

4. An example of the interaction of sustainability and environmental policies

We give here an explicit example of an economy where (asymptotic) sustainability and environmental policies are distinct in both form and strength, and also interact. The economy is a variant on Stiglitz (1974), being closed, with a known, non-renewable resource, no emissions, and just one externality, from the resource stock's role in a Cobb-Douglas production function with exogenous technical progress at rate ν (the last two features were absent from the simple model in Section 3.1):

$$F(K,R,\bar{S},t) = K^{\alpha}R^{\gamma}\bar{S}^{\chi}e^{\nu t} = C + \dot{K}; \quad 0 < \alpha,\gamma,\chi < 1;\ \alpha+\gamma+\chi \leq 1;\ \nu > 0 \qquad [17]$$

Utility is isoelastic and purely materialistic:

$$U(C) = C^{1-\eta}, \quad 0 < \eta < 1. \qquad [18]$$

The utility discount rate ρ is a positive constant. To ensure respectively that the welfare integral converges, and that socially optimal utility declines asymptotically (and hence that achieving sustainability is not an automatic side-effect of implementing environmental policy), we assume

$$(1-\alpha)\rho > (1-\eta)\nu \quad \text{and} \quad \rho\gamma > \nu. \qquad [19]$$

We denote asymptotic growth rates as $g_X := g\langle X\rangle := \lim_{t\to\infty}\dot{X}/X$ for any variable X. Since the resource is non-renewable, $\dot{S} = -R$, hence $g_S = g_R < 0$ and $R = g_R S$. Appendix 2 computes three asymptotic, balanced growth paths for this economy: the socially optimal path, the privately optimal path with sustainability policy only, and the privately optimal path with both sustainability and environmental policies.[11] For such a comparison, we cannot define sustainability as effectively moving to a "sustainability discount rate" σ, since this applies only if sustainability is achieved efficiently, which will not happen with the sustainability-only policy. The sustainability goal will therefore be defined as achieving constant utility ($g_C = 0$). The consumption growth rate g_C on the three paths is respectively:

Socially optimal path

$$g_C = (\nu-\rho\gamma) / [1-\alpha-(1-\eta)\gamma] \quad (< 0 \text{ from [19]}) \qquad [20]$$

Privately optimal path with sustainability policy (τ^C) only

$$g_C = [\nu-(\rho+\dot{\tau}^C/(1+\tau^C))(\gamma+\chi)] / [1-\alpha-(1-\eta)(\gamma+\chi)] \qquad [21]$$

Privately optimal path with sustainability policy (τ^C) and environmental policy ($-\tau^S$)

$$g_C = [\nu-(\rho+\dot{\tau}^C/(1+\tau^C))\gamma] / [1-\alpha-(1-\eta)\gamma] \qquad [22]$$

11. In all three cases, one cannot tell whether utility rises or falls in the (potentially long) period before development comes close to the asymptotic, balanced growth path.

The required strength of sustainability policy (i.e. to make $g_C = 0$) is lower if environmental policy is already in place: $-\dot{\tau}^C/(1+\tau^C) = \rho - \nu/\gamma$ from [22], instead of the larger $-\dot{\tau}^C/(1+\tau^C) = \rho - \nu/(\gamma+\chi)$ from [21]. So *environmental policy makes sustainability policy easier* here. The amount of difference made by environmental policy is related to χ, the strength of the stock externality in the production function.

Unfortunately, we cannot show analytically that a stronger sustainability policy, by in effect discounting future environmental quality less, increases the required strength of environmental policy. Appendix 2 shows that the latter policy is a resource stock subsidy $-\tau^S = F_S = \chi F/S$, which changes over time. One would suspect, though, that such an effect could be demonstrated numerically, thus matching the finding in Howarth and Norgaard's (1992) overlapping generations model.

5. Two extra results in more specialised economies

5.1 The powerlessness of resource incentives alone to prevent falling utility

We consider here a special case, where the economy is closed, there is no resource renewal ($G = 0$, so $\dot{S} = -R$), the discount rate ρ is (crucially) a positive constant, and there is no amenity effect of emissions ($U_E = 0$). Since the resource is finite and non-renewable, the resource depletion rate R must be asymptotically zero. With $F = F(K,R)$ only (unlike in Section 4, where there is exogenous technical progress at rate ν) and $F_{KR} > 0$, it seems reasonable to make this crucial:

Assumption: On the privately optimal path with policy intervention,

$$\lim_{t\to\infty} F_K =: \xi, \quad 0 \le \xi < \rho. \qquad [23]$$

That is, no matter what policy instruments are used, the privately optimal return on capital F_K (the competitive interest rate) eventually falls below ρ. (Proving the exact conditions under which [23] holds is complex even for simple economies, as shown by Pezzey and Withagen (1998).)

We choose here to consider resource incentives on their own, which the analysis of Section 3 showed to be inappropriate for achieving sustainability efficiently. But suppose we are willing to achieve sustainability inefficiently, so that the Section 3 results do not apply. Let us then define sustainability as non-declining utility; such a specific and therefore debatable goal is necessary, because the general device of a "sustainability" discount rate path $\sigma(t)$ cannot be used. We establish:

Proposition: Under the above conditions, no matter what $\tau^R(t)$ and $\tau^S(t)$ schedules the government creates as policy interventions, if these are the only interventions, then $\lim_{t\to\infty}\dot{U} < 0$. In other words, resource depletion and resource stock incentives τ^R(t) and τ^S(t) are powerless on their own to prevent unsustainability in the form of asymptotically falling utility.

Proof: From Appendix 3, the time derivative of utility on the policy path under the above conditions with only τ^R and τ^S as interventions is

$$\dot{U} = [(F_K-\rho)U_C - R(U_{CS}+\eta U_S/C)]\ C\ /\ \eta, \qquad [24]$$

in which resource incentives τ^R and τ^S do not appear. [23], with $U_C > 0$ from [5], then means that $\lim_{t\to\infty}(F_K-\rho)U_C < 0$. Also $U_{CS} \geq 0$ and $U_S > 0$ from [5], so the stock amenity term $-R(U_{CS}+\eta U_S/C) < 0$. So both terms in [24] < 0 asymptotically, hence $\lim_{t\to\infty}\dot{U} < 0$. Q.E.D.

Of course, resource taxes and subsidies will have some effect on $\dot{U}$, via the return on capital $F_K(K,R)$, as seen from the Hotelling rule for the privately optimal path with intervention calculated in Appendix 1(b):

$$F_K = [(d/dt)(F_R - \tau^R - \tau^E E_R) - \tau^S] \;/\; (F_R - \tau^R - \tau^E E_R) \qquad [25]$$

However, given the assumption in [23], no sustained (i.e. asymptotic) effect of τ^R and/or τ^S on F_K is possible. Intuitively, τ^R and τ^S can raise $F_K(K,R)$ only by giving an incentive to *increase* the resource flow R, but such a non-vanishing R can be sustained for only a finite time by a finite, non-renewable stock S_0.

The only way to raise $\dot{U}$ by a sustained, finite amount is to use a instrument such as a falling consumption tax as in [16], with $\sigma \le \xi$. The combination of this and resource policies is then efficient, and we can revert to the device of a sustainability discount rate. We then have $\lim_{t\to\infty}\dot{\tau}^C/(1+\tau^C) \le -(\rho-\xi) < 0$, and Appendix 4 shows that this means τ^C must ultimately be a 100% subsidy:

$$\Rightarrow \;\; \lim_{t\to\infty}\tau^C = -1 \qquad [26]$$

So the sustainability policy eventually requires lump sum taxes to pay for this subsidy. As an example, one can show that a consumption tax/subsidy path $\tau^C(t) = [1+((1/\alpha)-1)\bar{C}/K_0]^{\alpha/(1-\alpha)}e^{-\rho t} - 1$, which $\to -1$ as $t \to \infty$, converts the welfare-maximising path of the economy with constant discount rate ρ and $F(K,R) = K^\alpha R^{1-\alpha} = \dot{K} + C$, into the Solow (1974) path of maximum constant consumption, $C(t) = \bar{C} := \alpha\{K_0^{2\alpha-1}[(2\alpha-1)S_0]^{1-\alpha}\}^{1/\alpha}$ for all t.

5.2 The separation of production and resource management from sustainability policy in a small open economy with no amenity

Here we consider a variant of our Section 3 model, where the economy is now small and open, and there are no environmental amenity effects ($U_E = U_S = 0$), leaving $F_E < 0$ as the only environmental effect. (One could also have a stock externality on production, $F_S > 0$, and still reach the result below; the crucial condition is for consumption to be the sole determinant of utility.) Making the economy small and open means adding extra variables to the model. The resource input to production (and, we also assume, to emissions) is now not total resource extraction R, but domestic resource use R^d, where $R^x := R - R^d$ is net resource exports. To account for net imports M of the consumption-investment good, instead of [4] we have

$$F[K,R^d,E(R^d,a)] + M = C + \dot{K} + a \qquad [27]$$

The economy has a stock K^f of foreign capital (possibly negative, meaning debt) which earns a return at the world interest rate r, while its net resource exports R^x are sold at world prices Q^x. Because the economy is small, both r and Q^x are exogenous, but may vary over time. Foreign capital grows as:

$$\dot{K}^f = rK^f + Q^x R^x - M; \quad K^f(0) = K^f_0, \text{ given.} \qquad [28]$$

Extra control variables are now M, and R^d and R^x instead of R. The Hamiltonian for the optimal sustainable economy is changed from [7] to

$$H = U(C) + \Psi^K[F(K,R^d,E(R^d,a))+M-C-a] \\ + \Psi^f(rK^f+Q^xR^x-M) + \Psi^S[G(S)-R^d-R^x] \qquad [29]$$

The result we seek can be obtained without even considering the intervention policies which would make the privately optimal path follow the optimal sustainable path. Appendix 5 shows that the first order conditions determining the optimal sustainable path are

$$1/E_a(R^d,a) = F_E(K,R^d,a) \qquad [30]$$

$$Q^x = F_R(K,R^d,a) + F_E(K,R^d,a)E_R(R^d,a) \qquad [31]$$

$$r = F_K(K,R^d,a) \qquad [32]$$

$$r - G_S(S) = \dot{Q}^x/Q^x \qquad [33]$$

$$r = \sigma - \dot{U}_C(C)/U_C(C) \qquad [34]$$

This economy can therefore be separated into two parts. Because of the exogeneity of the world interest rate r and resource price Q^x, the four variables K, R^d, S and a are in principle fully determined by the four equations [30]-[33], as are then production $F(.)$, emissions $E(.)$ and resource exports $R^x(.)$. So *the open economy's production and resource management decisions are entirely unaffected by any goal of sustainability policy*, as represented by the sustainability discount rate σ in [34]. σ affects consumption C, which then also affects the economy's net imports M (via [27]) and in turn its foreign capital K^f (via [28]), but nothing else. For completeness, Appendix 7 shows that, as in Section 3.4, the only independent policy instruments worth considering are an emissions tax τ^E, a resource stock subsidy $-\tau^S$ and a consumption tax τ^C, which are then respectively determined by [12], [14] and [16], but with $U_E = U_S = 0$.

The importance of the above separation result can be seen by supposing that a small, open economy, with no sustainability policy but a full environmental policy, would follow a socially optimal path where its natural resources are eventually completely depleted, and where development is unsustainable. Implementing a sustainability policy will then make *no difference* to how resources and production are managed in this economy. Its only result will be less consumption and more saving, with all the saving being invested in foreign capital. This is essentially another version of Fisher's (1930/1954, p271) "separation theorem", where the separation of consumption and saving decisions from depletion and production decisions follows from the exogeneity of the interest rate and resource prices.

This scenario, of achieving sustainability despite stripping domestic resources by investing the proceeds abroad, would contradict the claim that preventing unsustainability requires *resource* policies. This claim, based on assumed non-substitutability of humanmade capital for natural resources, and promoted by Pearce (1988), Daly (1990) and many other authors since as one of the cardinal rules of sustainability, is that domestic natural resources must be conserved in some way. However, our theoretical refutation of this, and derivation of what could in some cases be a "strip resources and invest abroad" policy, is not intended to recommend the latter in practice. Such a policy would be optimal only in the highly unlikely event that neither resources nor emissions have any direct amenity value; that capital will always be substitutable for resources in domestic production; that all this is known with certainty; and that few other countries are planning to adopt the same policy, so that no fallacy of composition occurs. If all countries followed the policy, there would obviously be no "abroad" left to conserve natural resources and accept incoming investments (a similar point is made by Brekke 1997, p62).

6. Conclusions

Using a simple, representative-agent, neoclassical model of a dynamic economy, we have shown how environmental policy and sustainability policy, terms used interchangeably in much policy debate, can be theoretically quite distinct. As defined here, they have both different goals, and different instruments needed to achieve these goals. Environmental policy is dynamic, government intervention to maximise intertemporal social welfare based on the individual’s own discount rate path, by internalising the social values of "environmental" stocks and flows that agents ignore (externalise) when they privately maximise welfare. Sufficient instruments to achieve this are first best incentives (taxes or subsidies, with any costs or revenues neutralised by lump sum transfers) that are applied directly to the stocks and flows that are the source of externalities, and that are equal to environmental values in equilibrium. Any incentives applied to intermediate variables, like taxes on resource depletion, or subsidies for current spending on emissions abatement, are theoretically (though maybe not practically) redundant. It can also be shown that these conclusions are unaffected by extending the analysis to include cumulative pollutants, resource discovery and extraction costs, trade in goods and resources, abatement capital equipment, and exogenous technical progress.

By contrast, sustainability policy aims to achieve some improvement in intergenerational equity, whether a general shift to a lower path of the utility discount rate over time, or a specific goal such as making utility forever constant, non-declining or sustainable. We assumed, without any formal analysis, that such equity could not be represented in the original social welfare function based on individual preferences, and that people may support governments that try to achieve intergenerational equity with a sustainability policy which prevents social welfare maximisation. If sustainability policy is combined with environmental policy, we call the result an optimal sustainability policy; and because the resulting economy is efficient, the sustainability policy component can always be represented as a shift from the representative agent's individual utility discount rate to some other, probably lower, "sustainability discount rate" path. If however sustainability policy acts on its own, it will be inefficient in an economy with externalities, and cannot be represented this way. For both efficient and inefficient cases, given the absence of explicit intergenerational transfers or directly manipulable interest rates in our model, the sustainability policy instrument is an incentive such as a falling consumption tax, or a capital or investment subsidy, that affects the consumption-investment split over time.

Sustainability policy will clearly interact with environmental policy, but it is hard to say how in general. We showed analytically, in an asymptotic, Cobb-Douglas, capital-resource economy, how implementing environmental policy lowers the required strength of sustainability policy. The fact that sustainability policy requires incentives affecting the consumption-investment choice was also illustrated by results in more restricted economies. If the economy is closed with a constant discount rate and non-renewable but no renewable resources, then the return to capital is likely to fall below the discount rate, which means that resource incentives are ultimately powerless to prevent unsustainability in the form of asymptotically declining utility. Only consumption-related incentives, ultimately subsidies, will suffice. If the economy is small and open with no environmental amenity effects, then sustainability policy has absolutely no general equilibrium effect on resource management or domestic production. It is then theoretically possible for a small economy, acting in isolation, to achieve sustainable development while stripping its domestic natural resources down to zero, as long as its consumption is restrained, and enough is invested in foreign capital stocks.

These results do not suggest that in a more realistic policy context, sustainability and environmental policies can and should be considered in separate, watertight compartments. The analysis is not at all complete. Many important topics have been ignored, and remain for further work. These include education and knowledge accumulation, international market power and strategic interactions, cross-border environmental effects, second-best policy instruments, general taxation and public expenditure (including on intergenerational trust funds), and above all the profound uncertainty about the limits to the substitutability of human-made capital for environmental resources. However, our analysis does suggest adding a rather different focus than has appeared to date in most neoclassical economic literature on sustainability, which has stressed definition, justification, measurement and accounting, rather than policy intervention. The focus is also different than most of the relevant ecological economic literature, which has almost exclusively stressed action to protect environmental resources, based on an assumption of imminent limits to capital-resource substitutability. To be complete, sustainability analysis also needs to pay attention to policy intervention that will encourage adequate saving and investment.

Appendix 1

In parts (a) and (b) we respectively calculate an efficient and sustainable path, and the privately optimal path with policy interventions, both from Section 3, on the presumption that interventions can be found that make the two paths identical in terms of non-policy variables such as consumption, utility, capital and resources. Part (c) compares the two paths, to find what the intervention instruments must be.

(a) An efficient and sustainable path

From the Hamiltonian [7], an interior solution which maximises "sustainable" welfare $W^{\sigma}(0)$ in [10] subject to [2]-[5] will satisfy the first order conditions:

$$\partial H/\partial C = 0 = U_C - \Psi^K$$

$$\Rightarrow \quad \Psi^K = U_C$$

$$\partial H/\partial a = 0 = U_E E_a + \Psi^K(F_E E_a - 1)$$

$$\Rightarrow \quad (U_E/U_C + F_E)E_a = 1 \qquad \text{[A1]}$$

$$\partial H/\partial R = 0 = U_E E_R + \Psi^K(F_R + F_E E_R) - \Psi^S$$

$$\Rightarrow \quad \Psi^S = U_C\,[F_R + (U_E/U_C + F_E)E_R] =: U_C\,[F_R - \lambda], \text{ say} \qquad \text{[A2]}$$

$\partial H/\partial K = \sigma\Psi^K - \dot{\Psi}^K = \Psi^K F_K$

$\Rightarrow \quad \dot{U}_C/U_C = \sigma - F_K$ [A3]

$\partial H/\partial S = \sigma\Psi^S - \dot{\Psi}^S = U_S + \Psi^S G_S$

$\Rightarrow \quad \dot{\Psi}^S/\Psi^S = \sigma - G_S - U_S/\Psi^S$, which using [A2] becomes

$\dot{U}_C/U_C + (\dot{F}_R - \dot{\lambda})/(F_R - \lambda) = \sigma - G_S - (U_S/U_C)/(F_R - \lambda)$ [A4]

$\Rightarrow \quad (\dot{F}_R - \dot{\lambda})/(F_R - \lambda) = F_K - G_S - (U_S/U_C)/(F_R - \lambda)$, [A5]

which is the form of Hotelling's rule for this economy.

(b) The privately optimal path with policy intervention

From the Hamiltonian [11], the first order conditions satisfied by an interior solution of the privately optimal path with intervention are:

$\partial\tilde{H}/\partial C = 0 = U_C - \tilde{\Psi}^K(1+\tau^C)$

$\Rightarrow \quad \tilde{\Psi}^K = U_C/(1+\tau^C)$

$\partial\tilde{H}/\partial a = 0 = -\tilde{\Psi}^K(1+\tau^a+\tau^E E_a)$

$\Rightarrow \quad \tau^a + \tau^E E_a = -1$ [A6]

$\partial\tilde{H}/\partial R = 0 = \tilde{\Psi}^K(F_R - \tau^R - \tau^E E_R) - \tilde{\Psi}^S$

$\Rightarrow \quad \tilde{\Psi}_S = \tilde{\Psi}_K\,(F_R - \tau^R - \tau^E E_R) =: [U_C/(1+\tau^C)]\,(F_R - \tilde{\lambda})$, say [A7]

$\partial\tilde{H}/\partial K = \rho\tilde{\Psi}^K - \dot{\tilde{\Psi}}^K = \tilde{\Psi}^K F_K$

$\Rightarrow \quad \dot{U}_C/U_C - \dot{\tau}^C/(1+\tau^C) = \rho - F_K$ [A8]

$\partial\tilde{H}/\partial S = \rho\tilde{\Psi}^S - \dot{\tilde{\Psi}}^S = -\,\tilde{\Psi}^K\tau^S$

$\Rightarrow \quad \dot{\tilde{\Psi}}^S/\tilde{\Psi}^S = \rho + \tau^S\tilde{\Psi}_K/\tilde{\Psi}_S$, which using [A7] becomes

$\dot{U}_C/U_C - \dot{\tau}^C/(1+\tau^C) + (\dot{F}_R - \dot{\tilde{\lambda}})/(F_R - \tilde{\lambda}) = \rho + \tau^S/(F_R - \tilde{\lambda})$ [A9]

$\Rightarrow \quad (\dot{F}_R - \dot{\tilde{\lambda}} - \tau^S)/(F_R - \tilde{\lambda}) = F_K$ [A10]

This is Hotelling's rule, and substituting from [A7] gives [25].

(c) Environmental and sustainability policies combined

We now calculate the policy interventions that will indeed make the above two paths identical as assumed. Consider first the abatement tax τ^a. It is reasonable to assume there must be an emissions tax ($\tau_E \neq 0$), because otherwise the Hamiltonian [11] is a linear function of a, and so does not give an interior solution for a. So while an abatement spending tax could be part of the policy solution, it cannot fully substitute for an emissions tax. If [A1] and [A6] are to represent the same path of development, then the obvious sufficient (but not necessary) instruments needed are then

$$\tau^E = -(U_E/U_C+F_E) = \lambda/E_R \text{ from [A2]} \qquad \text{which is [12],}$$

and $\tau^a = 0$ which is [13].

A non-zero abatement spending tax τ^a would prevent the emissions tax adopting the obvious and intuitive form in [12]. So theoretically, τ^a is redundant, though differences in monitoring costs may well mean that this instrument is not always to be dismissed in practice.

Similarly comparing [A3] and [A8] requires

$$-\dot{\tau}^C/(1+\tau^C) = \rho-\sigma \qquad \text{which is [16].}$$

Comparing [A9] and [A4] requires:

$$-\dot{\tau}^C/(1+\tau^C) + (\dot{F}_R-\dot{\tilde{\lambda}})/(F_R-\tilde{\lambda}) - (\dot{F}_R-\dot{\lambda})/(F_R-\lambda)$$
$$= \rho-\sigma + \tau^S/(F_R-\tilde{\lambda}) + G_S + (U_S/U_C)/(F_R-\lambda), \text{ which with [16]}$$

$$\Rightarrow \quad (\dot{F}_R-\dot{\tilde{\lambda}})/(F_R-\tilde{\lambda}) - (\dot{F}_R-\dot{\lambda})/(F_R-\lambda) - \tau^S/(F_R-\tilde{\lambda})$$
$$= [(U_S/U_C)+(F_R-\lambda)G_S] \,/\, (F_R-\lambda)$$

The obvious sufficient (though not necessary) solution is if

$\lambda = \tilde{\lambda} = \tau^R + \lambda$ (from [A7] and [12]), in which case

$\tau^R = 0,$ which is [15],

and $-\tau^S \quad = U_S/U_C + (F_R-\lambda)G_S$

$= U_S/U_C + [F_R+(U_E/U_C+F_E)E_R]G_S$ which is [14].

Appendix 2

Here we compute three asymptotic, balanced growth paths for the economy in Section 4: the socially optimal path, the privately optimal path with sustainability policy only, and the privately optimal path with both sustainability and environmental policies. From [17], production, capital and consumption all grow at the same asymptotic rate as each other:

$$g_F = \alpha g_K + (\gamma+\chi)g_R + \nu = g_C = g_K \;\Rightarrow\; (1-\alpha)g_C = (\gamma+\chi)g_R + \nu \qquad \text{[A11]}$$

The socially optimal path

[A3], [18] $\Rightarrow\; -\eta g_C = \rho - F_K$ [A12]

[A5] with $\lambda = G_S = U_S = 0$, but with an extra term $-F_S/F_R$ on the R.H.S.

$\Rightarrow\; \dot{F}_R/F_R = g\langle\gamma F/R\rangle = F_K - F_S/F_R$ [A13]

$\Rightarrow\; g_C - g_R = F_K - (\chi F/S)/(\gamma F/R)$

$\Rightarrow\; g_C = F_K + (1+\chi/\gamma)g_R$ [A14]

[A12], [A14] and [A11]

$\Rightarrow\; (1-\eta)g_C = \rho + (1+\chi/\gamma)g_R = \rho + [(1-\alpha)g_C-\nu]/\gamma$

$\Rightarrow\; [(1-\eta)\gamma-(1-\alpha)]g_C = \rho\gamma - \nu$

$\Rightarrow\; g_C = (\nu-\rho\gamma) / [1-\alpha-(1-\eta)\gamma] < 0$ from [19] [20]

The privately optimal path with sustainability policy (τ^C) only

[A11] and [A12] still hold, while F_S (= $\chi F/S$) is ignored, so [A14] becomes $\quad g_C = F_K + g_R$ [A15]

[A8], [18] $\Rightarrow\; -\eta g_C - \dot{\tau}^C/(1+\tau^C) = \rho - F_K$ [A16]

[A15], [A16] and [A11]

$$\Rightarrow\ (1-\eta)g_C - \dot{\tau}^C/(1+\tau^C) = \rho + [(1-\alpha)g_C - \nu]/(\gamma+\chi)$$

$$\Rightarrow\ [(1-\eta)(\gamma+\chi)-(1-\alpha)]g_C = [\rho+\dot{\tau}^C/(1+\tau^C)](\gamma+\chi) - \nu$$

$$\Rightarrow\ g_C = [\nu-(\rho+\dot{\tau}^C/(1+\tau^C))(\gamma+\chi)] \,/\, [1-\alpha-(1-\eta)(\gamma+\chi)] \qquad [21]$$

The privately optimal path with sustainability policy (τ^C) and environmental policy ($-\tau^S$)

From [A10] with $\tilde{\lambda} = 0$, and [A13], the environmental policy is a resource stock subsidy $-\tau^S = F_S = \chi F/S$ (not constant), which causes [A14] to be reinstated, while [A16] still holds. So [A11], [A14] and [A16]

$$\Rightarrow\ (1-\eta)g_C - \dot{\tau}^C/(1+\tau^C) = \rho + [(1-\alpha)g_C - \nu]/\gamma$$

$$\Rightarrow\ [(1-\eta)\gamma-(1-\alpha)]g_C = [\rho+\dot{\tau}^C/(1+\tau^C)]\gamma - \nu$$

$$\Rightarrow\ g_C = [\nu-(\rho+\dot{\tau}^C/(1+\tau^C))\gamma] \,/\, [1-\alpha-(1-\eta)\gamma] \qquad [22]$$

Appendix 3

Sustainability-only policy in Section 5.1

We calculate an expression for the rate of change of utility when $U_E = 0$:

$\dot{U}_C = U_{CC}\dot{C} + U_{CS}\dot{S}$

$\Rightarrow\ (U_{CC}/U_C)\dot{C} + U_{CS}\dot{S}/U_C = \dot{U}_C/U_C$

$\quad = \dot{\tau}^C/(1+\tau^C) + \rho - F_K$ from [A8]

Using $U_{CC}/U_C = -\eta(C)/C$, this means that

$(-\eta/C)\dot{C} = \rho - F_K - U_{CS}\dot{S}/U_C$

$\Rightarrow \dot{C} = [\ F_K - \rho - \dot{\tau}^C/(1+\tau^C) + U_{CS}\dot{S}/U_C\ ]\ C/\eta$

$\Rightarrow \dot{U} = U_C\dot{C} + U_S\dot{S}$

$\quad = [(F_K-\rho)U_C + U_{CS}\dot{S}]C/\eta + U_S\dot{S}$

$\quad = [(F_K-\rho)U_C - R(U_{CS}+\eta U_S/C)]\ C\ /\ \eta$ which is [24].

Appendix 4

To prove for Section 5.1: If $\dot{\tau}^C/(1+\tau^C) < 0$ and is bounded away from zero after some time, then $\lim_{t\to\infty}\tau^C = -1$. *Proof:* the subsidy rate $\tau^C > -1$, or else an individual's desired consumption would be unbounded. Hence $\dot{\tau}^C < 0$, to make $-\dot{\tau}^C/(1+\tau^C) > 0$. So $\lim_{t\to\infty}\tau^C = -1+z$ for some finite $z \geq 0$, and $\lim_{t\to\infty}\dot{\tau}^C = 0$. But then $\lim_{t\to\infty}[-\dot{\tau}^C/(1+\tau^C)] = 0/z$, and $\lim_{t\to\infty}[-\dot{\tau}^C/(1+\tau^C)] > 0$ by assumption. Hence $z = 0$.

Appendix 5

Results for the small open economy in Section 5.2

From the Hamiltonian [29], the first order conditions of the optimal sustainable path are

$\partial H/\partial C = 0 = U_C - \Psi^K$

$\Rightarrow \quad \Psi^K = U_C$

$\partial H/\partial a = 0 = \Psi^K(F_E E_a - 1)$

$\Rightarrow \quad 1/E_a(R^d,a) = F_E(K,R^d,a)$ which is [30]

$\partial H/\partial R^d = 0 = \Psi^K(F_R + F_E E_R) - \Psi^S$

$\Rightarrow \quad \Psi^S = U_C(F_R + F_E E_R)$

$\partial H/\partial M = \Psi^K - \Psi^f = 0 \quad \Rightarrow \quad \Psi^f = \Psi^K$

$\partial H/\partial R^x = 0 = \Psi^f Q^x - \Psi^S \quad \Rightarrow \quad \Psi^S = U_C Q^x$ [A17]

and $Q^x = F_R(K,R^d,a) + F_E(K,R^d,a)E_R(R^d,a)$ which is [31]

$\partial H/\partial K = \sigma\Psi^K - \dot{\Psi}^K = \Psi^K F_K \quad \Rightarrow \quad \dot{U}_C/U_C = \sigma - F_K$

$\partial H/\partial K^f = \sigma\Psi^f - \dot{\Psi}^f = \Psi^f r \quad \Rightarrow \quad r = F_K(K,R^d,a)$ which is [32]

and $r = \sigma - \dot{U}_C(C)/U_C(C)$ which is [34]

$\partial H/\partial S = \sigma\Psi^S - \dot{\Psi}^S = \Psi^S G_S \quad \Rightarrow \quad \sigma - G_S = \dot{\Psi}^S/\Psi^S = \dot{U}_C/U_C + \dot{Q}^x/Q^x$

Use [A17], [34] $\quad \Rightarrow \quad r - G_S(S) = \dot{Q}^x/Q^x$ which is [33]

Appendix 6: Formulae for investment tax instead of consumption tax

This explains two claims made in Section 3.2 just before equation [8]:

(a) "the consumption tax and the investment tax can be shown to be substitutes for each other, and expressions for the first are simpler than for the second";

(b) "...a tax on the capital stock...is another, and in fact algebraically simpler, substitute for a consumption tax, though arguably much harder to administer."

We explain (b) first, by adding a capital tax τ^K to the set of policy instruments. The Hamiltonian for the privately optimal path with policy intervention is then:

$$H = U(C,\bar{S},\bar{E}(R,a)) + \tilde{\Psi}^K[F(K,R,\bar{E}(R,a))-C-a]$$
$$- \tilde{\Psi}^K[\tau^C C+\tau^K K+\tau^a a+\tau^R R+\tau^S S+\tau^E E(R,a)-\Omega] + \tilde{\Psi}^S[G(\bar{S})-R].$$

This results in [A8] and [16] being replaced by

$$\dot{U}_C/U_C - \dot{\tau}^C/(1+\tau^C) = \rho - F_K + \tau^K, \text{ and}$$
$$-\dot{\tau}^C/(1+\tau^C) - \tau^K = \rho-\sigma, \qquad \text{[R1]}$$

showing that a capital subsidy $-\tau^K = \rho-\sigma$ can in theory substitute perfectly for a falling consumption tax $-\dot{\tau}^C/(1+\tau^C) = \rho-\sigma$ as an instrument of sustainability policy.

In explaining (a), the replacement of a consumption tax τ^C by an investment tax τ^I, it is simplest to change from consumption C to investment I as a control variable. The individual then perceives a production split

$$F(K,R,\bar{E}(R,a)) = C+I+a + \tau^I I+\tau^K K+\tau^a a+\tau^R R+\tau^S S+\tau^E E(R,a) - \Omega, \qquad \text{[R2]}$$

so substituting for C from [R2] in the utility function means that the Hamiltonian $\tilde{H}$ for the policy intervention economy is

$$U[F(K,R,\bar{E}(R,a))-(1+\tau^I)I-a-\tau^K K-\tau^a a-\tau^R R-\tau^S S-\tau^E E(R,a)+\Omega, \bar{S}, \bar{E}(R,a)]$$
$$+ \tilde{\Psi}^K I + \Psi^S[G(\bar{S})-R].$$

Two first order conditions are then

$$\partial\tilde{H}/\partial I = 0 = -U_C(1+\tau^I) + \tilde{\Psi}^K$$
$$\Rightarrow \quad \tilde{\Psi}^K = (1+\tau^I)U_C, \quad \text{and}$$
$$\partial\tilde{H}/\partial K = \rho\tilde{\Psi}^K - \dot{\tilde{\Psi}}^K = U_C(F_K-\tau^K)$$
$$\Rightarrow \quad \dot{\tilde{\Psi}}^K/\tilde{\Psi}^K = \rho - (F_K-\tau^K)U_C/\tilde{\Psi}^K$$
$$\Rightarrow \quad \dot{U}_C/U_C + \dot{\tau}^I/(1+\tau^I) = \rho - (F_K-\tau^K)/(1+\tau^I). \qquad [R3]$$

Comparing [R3] and [32] gives

$$\dot{U}_C/U_C = \sigma - F_K = \rho - (F_K-\tau^K)/(1+\tau^I) - \dot{\tau}^I/(1+\tau^I)$$
$$\Rightarrow \quad \rho-\sigma = F_K[1/(1+\tau^I) - 1] + (\dot{\tau}^I-\tau^K)/(1+\tau^I)$$
$$= (\dot{\tau}^I-\tau^I F_K-\tau^K)/(1+\tau^I) \qquad [R4]$$

in which the investment tax plays a more complicated role than the consumption tax in [R1]. Note though that a capital subsidy $-\tau^K = \rho-\sigma$ on its own could again fulfil the required policy role.

Appendix 7: Confirming the form of the sustainability and environmental policies for the small open economy

The Hamiltonian for the privately optimal path with policy intervention (including taxes τ^d on domestic resource use and τ^x on resource exports for completeness) in the small open economy in Section 5.2 is

$$\tilde{H} = U(C)$$
$$+ \tilde{\Psi}^K[F(K,R^d,S,\bar{E}(R^d,a))+M-C-a-\tau^C C-\tau^a a-\tau^d R^d-\tau^x R^x-\tau^S S-\tau^E E(R^d,a)]$$
$$+ \tilde{\Psi}^f(rK^f+Q^x R^x-M) + \tilde{\Psi}^S[G(\bar{S})-R^d-R^x]$$

From this, the first order conditions for the privately optimal path with intervention are

$\partial\tilde{H}/\partial C = 0 = U_C - \tilde{\Psi}^K(1+\tau^C)$

$\Rightarrow \quad \tilde{\Psi}^K = U_C/(1+\tau^C)$

$\partial\tilde{H}/\partial a = 0 = -\tilde{\Psi}^K(1+\tau^E E_a)$

$\Rightarrow \quad \tau^a + \tau^E E_a = -1$ [R5]

$\partial\tilde{H}/\partial R^d = 0 = \tilde{\Psi}^K(F_R - \tau^d - \tau^E E_R) - \tilde{\Psi}^S$

$\Rightarrow \quad \tilde{\Psi}_S/\tilde{\Psi}_K = F_R - \tau^d - \tau^E E_R \quad \Rightarrow \quad \tilde{\Psi}^S = U_C(F_R - \tau^d - \tau^E E_R)/(1+\tau^C)$ [R6]

$\partial\tilde{H}/\partial M = \tilde{\Psi}^K - \tilde{\Psi}^f = 0 \quad \Rightarrow \quad \tilde{\Psi}^f = \tilde{\Psi}^K$

$\partial\tilde{H}/\partial R^x = 0 = -\tilde{\Psi}^K\tau^x + \tilde{\Psi}^f Q^x - \tilde{\Psi}^S \quad \Rightarrow \quad Q^x = \tau^x + F_R - \tau^d - \tau^E E_R$ [R7]

$\partial\tilde{H}/\partial K = \rho\tilde{\Psi}^K - \dot{\tilde{\Psi}}^K = \tilde{\Psi}^K F_K \quad \Rightarrow \quad \dot{U}_C/U_C - \dot{\tau}^C/(1+\tau^C) = \rho - F_K$

$\partial\tilde{H}/\partial K^f = \rho\tilde{\Psi}^f - \dot{\tilde{\Psi}}^f = \tilde{\Psi}^f r \quad \Rightarrow \quad r = F_K = \rho - \dot{U}_C/U_C + \dot{\tau}^C/(1+\tau^C)$ [R8]

$\partial\tilde{H}/\partial S = \rho\tilde{\Psi}^S - \dot{\tilde{\Psi}}^S = -\tilde{\Psi}^K\tau^S \quad \Rightarrow \quad \dot{\tilde{\Psi}}^S/\tilde{\Psi}^S = \rho + \tau^S\tilde{\Psi}_K/\tilde{\Psi}_S,$

which using [R6] and [R7] gives

$$(\dot{Q}^x - \dot{\tau}^x)/(Q^x - \tau^x) + \dot{U}_C/U_C - \dot{\tau}^C/(1+\tau^C) = \rho + \tau^S/(Q^x - \tau^x)$$

$\Rightarrow \quad r + \tau^S/(Q^x - \tau^x) = (\dot{Q}^x - \dot{\tau}^x)/(Q^x - \tau^x)$ [R9]

So comparing [30] and [R5] gives

$\tau^E = -F_E$ and $\tau^a = 0$ which are [12] with $U_E = 0$, and [13],

as the obvious (but not necessary) solution.

Comparing [31] and [R7] gives

$\tau^d = \tau^x = 0$ as the obvious (but not necessary) solution.

Comparing [34] and [R8] gives

$-\dot{\tau}^C/(1+\tau^C) = \rho - \sigma$ which is [16] again.

Comparing [33] and [R9] gives

$-\tau^S = Q^x G_S = (F_R + F_E E_R)G_S$ which is [14] with $U_E = U_S = 0$.

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